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VELA UNIFORM

PLOWSHARE PROGRAM, PROJECT GNOME

PROJECT 1.7

SHOCK SPECTRUM MEASUREMENTS

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NUCLEAR EXPLOSIONS—PEACEFUL APPLICATIONS
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SHOCK SPECTRUM MEASUREMENTS

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ABSTRACT

A total of twelve reed gages were installed to measure displacement shock spectra resulting from the Project Gnome underground nuclear explosion. Seven of the gages were installed on the ground surface at four locations out to a distance of 3000 feet from surface zero. All of these gages yielded usable records. Four of the gages were installed in the floor of the Gnome tunnel at two locations. Those at the 1033-foot range gave valid records; those at the 900-foot range were not recovered after the test. The one gage located underground at the International Minerals and Chemical Corporation (IMCC) mine, some nine miles distant, did not record any motion. The plotted displacement spectra showed the expected results in that displacements and peak accelerations decreased with increasing slant range for the surface gages. The vertical spectra were higher than the corresponding horizontal radial spectra for the surface gages. For the gages in the Gnome tunnel, the horizontal radial spectrum was higher than the vertical spectrum.

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CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

The objective of this project was to measure the displacement spectra of the ground shock caused by the Project Gnome three-kiloton (TNT equivalent) underground nuclear explosion. The spectra were to be measured at a number of surface and underground locations close to the explosion and at one underground location in the IMCC mine some nine miles away.

The objective of Project Gnome relative to ground shock was to expand the data on the characteristics of underground explosions to a new medium, rock salt (halite), which has marked differences from the tuff and alluvium in which previous underground explosion tests had been conducted. Gnome was the first nuclear explosion in the Plowshare Program which is devoted to research and development in peaceful applications of nuclear explosions.

1.2 BACKGROUND

The response shock spectra were first measured by TRW Space Technology Laboratories (STL) during Operation Plumbbob at the Nevada Test Site in 1957 (Reference 1). In these tests shock spectra resulting from air blast were measured on the surface of the ground. Similar measurements were made during Operation Hardtack at the Eniwetok Proving Ground in 1958 (Reference 2). Measurements of surface

shock spectra from surface high-explosive tests were obtained during 1960 and 1961 tests at the Suffield Experimental Station, Ralston, Alberta, Canada (References 3 and 4).

Spectra from underground nuclear explosions were measured at the Nevada Test Site during Operation Hardtack-Phase II in 1958 and during Operations Nougat, Sun Beam, Project Shoal, and other recent field tests (References 5 through 9).

The available shock spectrum data from Project Gnome were published in a preliminary report in June 1962 (Reference 10). At that time two gages had not been recovered from the Gnome access tunnel because of radioactivity. Recently, it was determined that these gages would not be recovered. Thus this final report contains only the data previously published.

CHAPTER 2

INSTRUMENTATION

The instrumentation used to make the ground shock spectrum measurements for Project Gnome consisted of twelve reed gages. This chapter provides background information on gage construction, theory, and field installation.

2.1 DESCRIPTION OF REED GAGES

The STL reed gages consist of a number of masses on cantilever springs or reeds mounted on a rigid base. The masses and spring constants of the reeds are so designed that their natural frequencies cover the range between 2 and 300 cycles per second (cps). The gage configuration, which was used for Project Gnome, has ten nominal reed frequencies of 3, 10, 20, 40, 80, 120, 160, 200, 250, and 300 cps. Figure 2.1 shows the 3, 20, and 40 cps reeds. Figure 2.2 shows the other side of the gage with the remaining reeds.

The masses, which move in one plane, have scribers in contact with a polished metal record plate. A thin layer of lamp black is deposited on the record plate prior to preshot installation by smoking it with a candle. When the gage base is subjected to ground shock, the reeds vibrate and the scribers record their maximum displacements on the record plate. After recovery of the record plates following the test, the displacements are measured. These measurements are converted to mass displacements by use of calibration factors which take into account such things as the location of the

scriber with respect to the center of the mass, the fact that the mass is distributed rather than a point mass, and slight variations in reeds due to manufacturing tolerances. This, then, provides the frequency-displacement data used for the shock spectrum measurements.

2.2 GAGE THEORY

The operation of the reed gages described in the previous section is based on theory which states that the response of a structure or piece of equipment to a given ground shock can be determined from the measured response of a reed having the same frequency and damping as the structure to the same ground shock. In effect, the reed is a model of the structure. Since in practice we may be interested in more than one frequency, the gages consist of a number of reeds covering a range of frequencies.

If a linear multi-degree-of-freedom structure attached to the ground is subjected to ground shock, the displacement of any point on the structure relative to the ground can be expressed as a sum of principal mode responses in a specific direction

$$u(t, x, y, z) = \sum q(t)\phi(x, y, z) \tag{2.1}$$

where

$u(t, x, y, z)$ = displacement of any point on the structure in a specific direction

$q(t)$ = generalized coordinate

$\phi(x, y, z)$ = free vibration mode shape in the specified direction

An upper limit of response can be obtained by assuming that all modes reach their peak values at the same time

$$u = \sum \left| q_{max} \phi \right| \tag{2.2}$$

For an acceleration input, it can be shown that for each mode

$$\ddot{q} + 2\beta\omega\dot{q} + \omega^2 q = -\gamma a(t) \tag{2.3}$$

where

q = generalized displacement relative to ground

$\dot{q}, \ddot{q}$ = derivatives with respect to time

ω = circular frequency of mode

β = ratio of damping to critical viscous damping

γ = kinematic factor = $\int p\phi \, dv / \int p\phi^2 dv$

p = mass distribution per unit volume

$a(t)$ = acceleration of ground as function of time

For small damping the solution of Equation 2.3 is

$$q_{max}(\omega, \beta) = \max_{t > 0} \left| \frac{\gamma}{\omega} \int_0^t a(\tau)\, e^{-\beta\omega(t-\tau)} \sin \omega (t - \tau)\, d\tau \right| \tag{2.4}$$

For an idealized single degree-of-freedom system such as a point mass on a weightless cantilever spring the equation of motion is

$$\ddot{Q} + 2\beta\omega\dot{Q} + \omega^2 Q = -a(t) \tag{2.5}$$

The reed gages with appropriate gage factors which account for stylus positions and distributed rather than point masses record the peak displacements as solutions of Equation 2.5. The plot of the peak

displacements of the reed masses relative to the base of the gage which is being accelerated versus the frequencies of the masses is called the displacement shock spectrum. It is defined as

$$D = Q_{max} = \max_{t > 0} \left| \frac{1}{\omega} \int_0^t a(\tau)\, e^{-\beta\omega(t-\tau)} \sin \omega(t - \tau)\, d\tau \right| \tag{2.6}$$

With the displacement spectrum, D, determined from the reed gage measurement the modal response of a structure having the same damping as the gage is given by

$$q_{max} = \gamma D \tag{2.7}$$

From Equations 2.2 and 2.7, the upper limit of response is given by

$$u = \sum |\gamma D \phi| \tag{2.8}$$

The pseudo-velocity shock spectrum is defined as

$$V = \omega D \tag{2.9}$$

This spectrum has the dimensions of velocity, but it does not represent the peak velocity of the mass relative to the base. It is useful, however, in the determination of an upper bound of strain energy in the structure.

The acceleration shock spectrum is defined as

$$A = \omega^2 D = \omega V \tag{2.10}$$

and can be shown to be the peak absolute acceleration of the mass for small values of damping, that is

$$A = \max \left| \ddot{Q} + a \right| \tag{2.11}$$

Equations 2.9 and 2.10 show that the three shock spectra are related quite simply by the frequency. These three spectra can be conveniently shown on a single plot such as that in Figures 3.1 through 3.5. For the scales shown therein the relationships between displacement, velocity, and acceleration shock spectra are

$$Ag = 2\pi fV = 4\pi^2 f^2 D \tag{2.12}$$

where

A = acceleration in g's

g = acceleration of gravity in inches/second^2

V = velocity in inches/second

D = displacement in inches

f = frequency in cps

It should be noted that the plotted response spectra are somewhat different than the ground motions themselves since they represent the response to the ground motion rather than the ground motion itself.

2.3 FIELD INSTALLATION

The twelve reed gages used for Project Gnome were located at seven gage stations. Four of the gage stations were on the surface

to the north of the surface zero point, two of the stations were in the Gnome tunnel, and one station was located underground in the IMCC mine. Figure 2.3 shows the location of the surface and the Gnome tunnel gage stations. The IMCC gage station was some nine miles to the north of the Gnome site.

The surface gage stations consisted of a concrete pad to which the protective canisters were bolted as shown in Figure 2.4. The reed gages were then bolted to the base of the canister. Figure 2.5 shows a gage secured in a canister in a horizontal position; Figure 2.6 shows a gage oriented vertically in a canister. Three of the surface gage stations, those at 75, 1000, and 2000 feet horizontal ranges, had both vertical and horizontal radial gages. The fourth gage station, that at 3000 feet horizontal range, had only a vertical gage.

The two gage stations in the Gnome tunnel were 900 feet and 1033 feet, respectively, from the Gnome explosion. These gages were also in protective canisters which were grouted in holes cut in the halite of the tunnel floor. At each of these gage stations both a vertical and a horizontal radial gage were installed.

The gage at the IMCC mine was oriented to measure horizontal radial motion. The canister was bolted to a concrete slab underground in the mine.

Table 2.1 lists pertinent location data for the gage stations.

TABLE 2.1 GAGE LOCATION DATA

GAGE STATION	GAGE NUMBER ⊄ ORIENTATION	HORIZONTAL DISTANCE FROM ZERO	COORDINATES	AZIMUTH FROM SURFACE ZERO	ELEVATION (MSL)	SLANT RANGE (FT.)	VERTICAL ANGLE
1.7-1	1 Vertical (V) 19 Horizontal Radial (H)	75	N 100,719 E 100,761	Due North	3395	1185	3° 38'
1.7-2	22 V 13 H	1000	N 101,316 E 100,020	N47° 47'W	3381	1540	40° 58'
1.7-3	21 V 12 H	2000	N 102,545 E 100,139	N18° 6'W	3367	2310	60° 3'
1.7-4	20 V	3000	N 103,615 E 100,349	N7° 53'W	3353	3210	69° 28'
1.7-5	9 V 11 H	900	N 100,073 E 100,064	S50° 41'W	2207	900	90°
1.7-6	14 V 17 H	1033	N 99,984 L 99,967	S50° 26'W	2207	1033	90°
IMCC Mine	5 H	Approximately 9 Miles (IMCC Mine)	-	-	-	-	-
-	Working Point Project Gnome	-	N 100,644 E 100,761	Elevation 2214 Ft.			

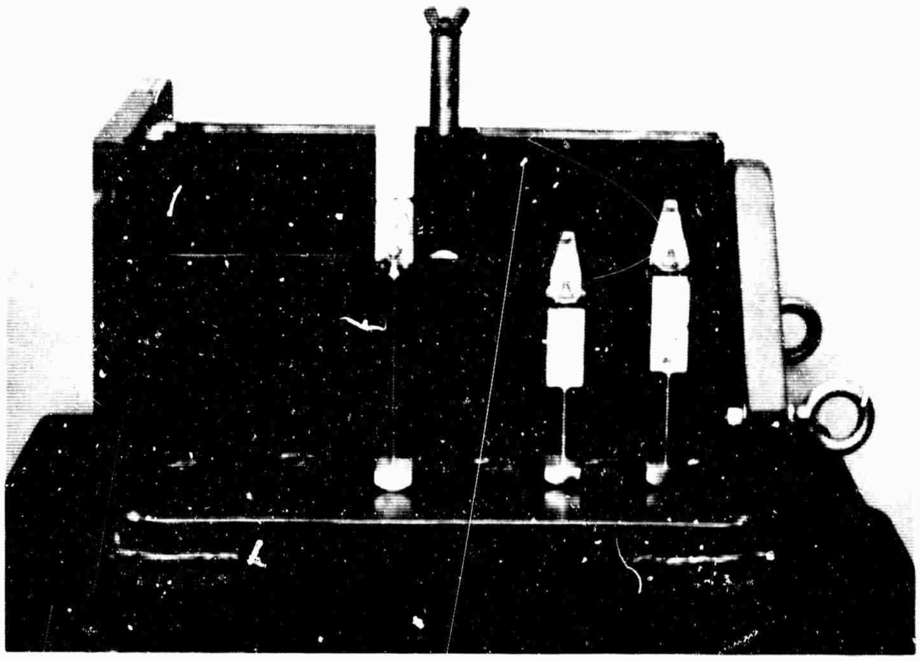

Figure 2.1 Reed gage showing 3, 40, and 20 cps reeds. (STL photo)

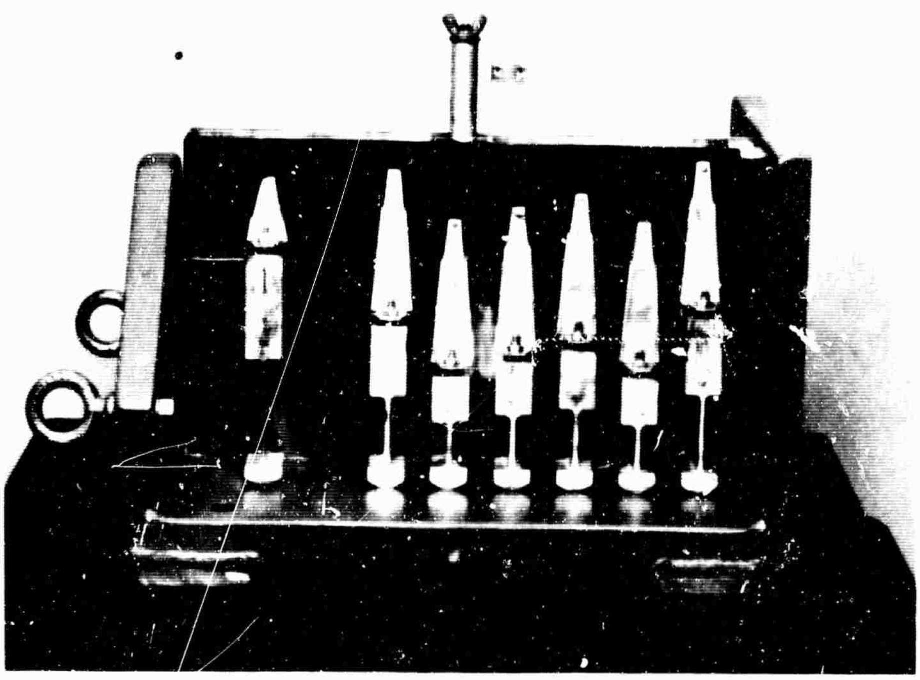

Figure 2.2 Reed gage showing 10, 120, 300, 200, 160, 250, and 80 cps reeds. (STL photo)

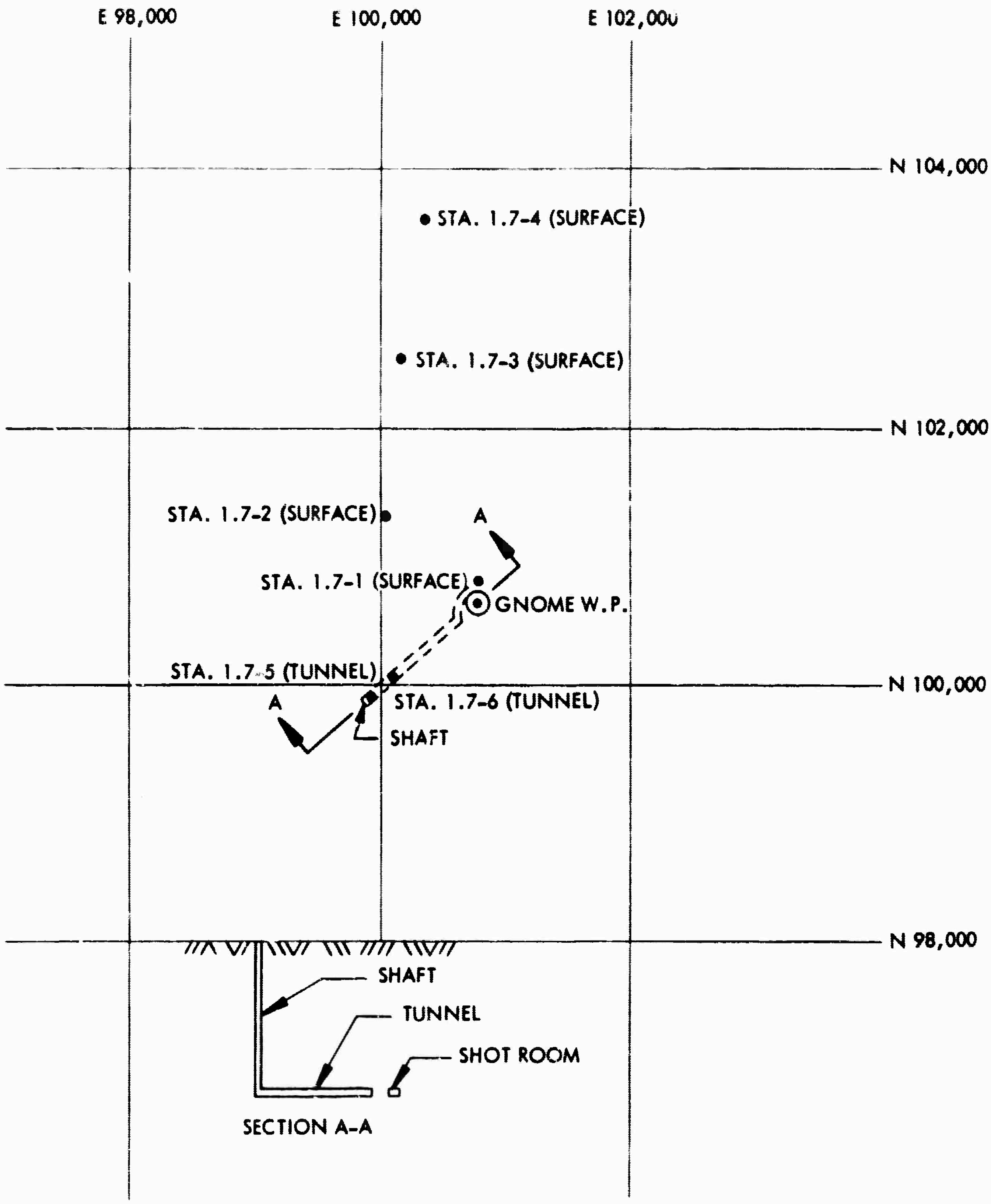

Figure 2.3 Layout of reed gage stations at Project Gnome site.

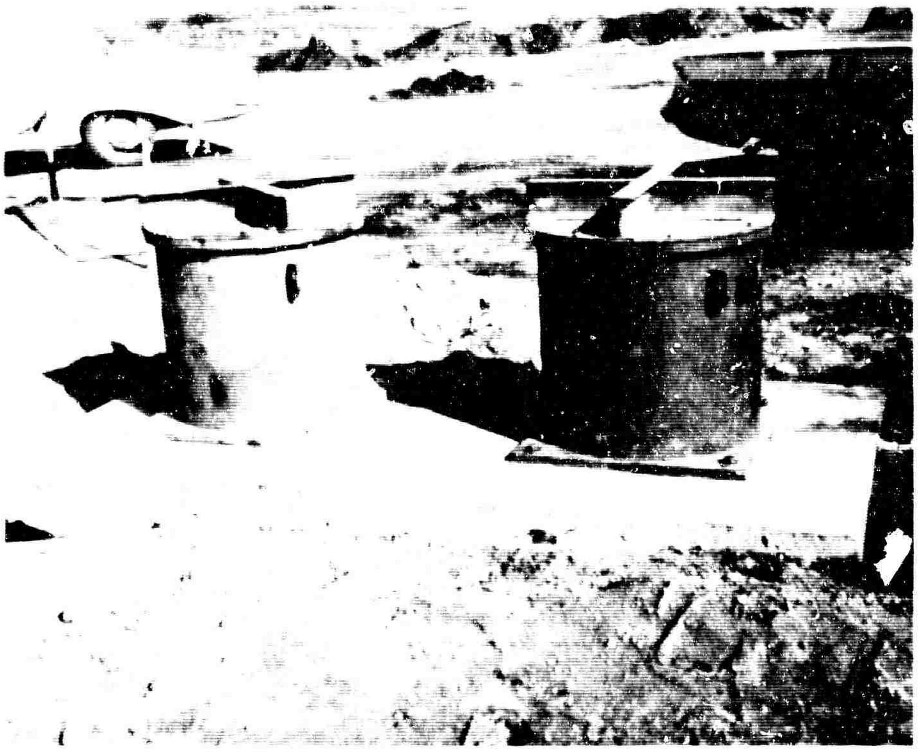

Figure 2.4 Surface gage station 75 feet from surface zero. (STL photo)

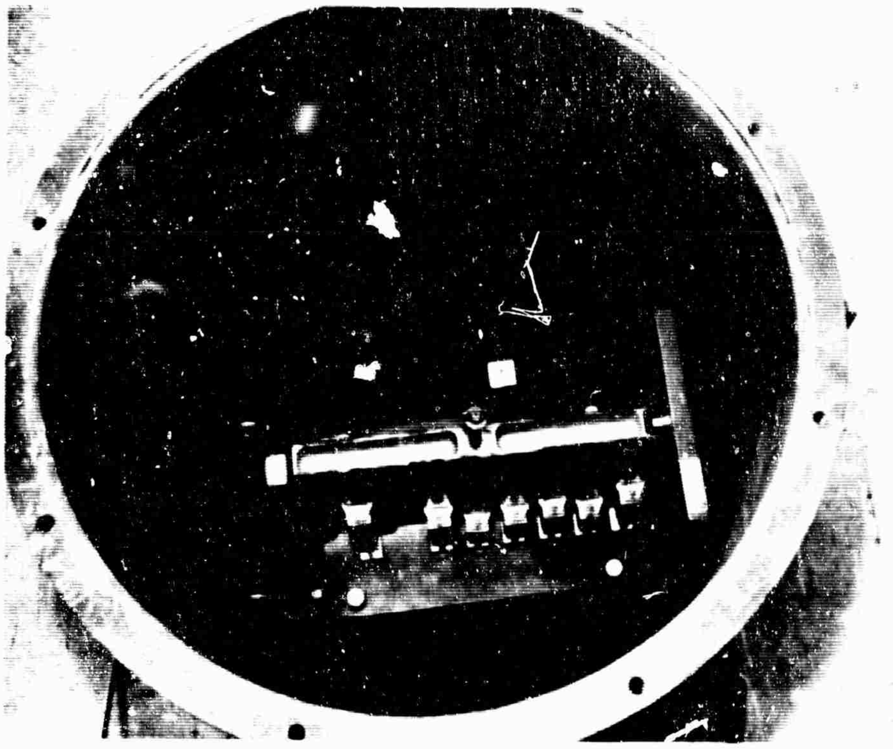

Figure 2.5 Gage installed horizontally in canister. (STL photo)

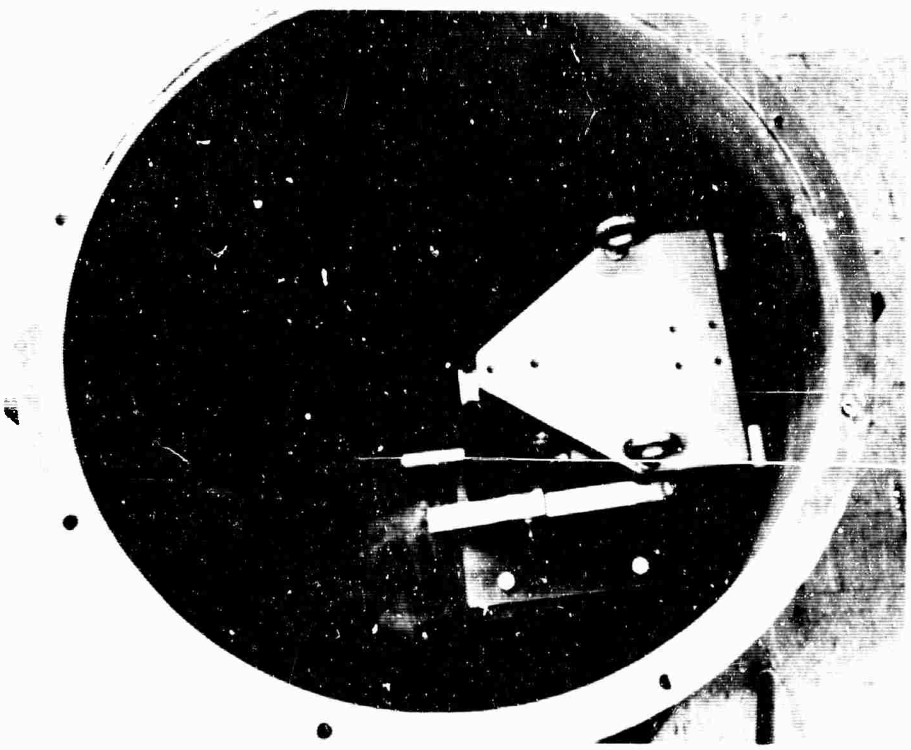

Figure 2.6 Gage installed vertically in canister. (STL photo)

CHAPTER 3

RESULTS AND DISCUSSION

3.1 DATA RECOVERY

Ten of the twelve gages were recovered after the shot. The two not recovered were those located at Station 1.7-6 at the 900-foot range in the floor of the Gnome tunnel.

The one gage which was installed underground at the IMCC mine was too distant to record any motion. The remaining nine gages all yielded usable records. Of the ninety possible data points from the nine gages a total of twelve points were lost because the reed failed, the trace was obscured, the trace was off the record plate, or the scribe missed the record plate. Six additional reed deflections were too small to be read. Seventy-two measurable deflection records were recovered. The frequency-displacement data which resulted from the reed gage records are presented in Table 3.1.

3.2 SHOCK SPECTRA

Shock spectra curves plotted from the frequency-displacement data are shown in Figures 3.1 through 3.5. At the three surface stations where there were both vertical and horizontal radial gages the vertical shock was the greater as shown in Figures 3.1, 3.2, and 3.3. As expected the spectra become higher for both vertical and horizontal shock as the range to the gage decreases. This range dependence is shown more clearly in Figure 3.6. This figure indicates that, in general, for the higher frequencies the displacements

attenuate more rapidly with increasing range than for the lower frequencies. This frequency effect is more apparent for the vertical response than for the horizontal radial response. The figure also shows that the rate of attenuation with range for the vertical response is greater than for the horizontal radial response.

Section 2.2 described the theory of the reed gage and pointed out that the absolute acceleration of the mass could be determined from the shock spectra plots. The peak accelerations from Figures 3.1 through 3.4 have been plotted in Figure 3.7 to show the attenuation with range. The only trend apparent from the limited data is the decreased rate of attenuation with increased range.

Since data are available from only one gage station in the Gnome tunnel, no analysis of range effects could be made for the underground gages. As might be expected, the spectrum for the horizontal radial shock in Figure 3.5 is higher than that for the vertical shock. Comparisons with the surface gage spectra would not be valid because the effects of the different geologic media between shot and gage locations and the effects of the ground surface are not clearly defined.

TABLE 3.1 FREQUENCY-DISPLACEMENT DATA

Station 1.7-1, 75 Ft. from Surface Zero, Horizontal Radial, Gage No. 19		Station 1.7-1, 75 Ft. from Surface Zero, Vertical, Gage No. 1		Station 1.7-2, 1000 Ft. from Surface Zero, Horizontal Radial, Gage No. 13		Station 1.7-2, 1000 Ft. from Surface Zero, Vertical, Gage No. 22		Station 1.7-3, 2000 Ft. from Surface Zero, Horizontal Radial, Gage No. 12		Station 1.7-3, 2000 Ft. from Surface Zero, Vertical, Gage No. 21	
f	d	f	d	f	d	f	d	f	d	f	d
3.3	3.36	3.2	NV	3.1	1.37	3.2	F	2.9	1.94	2.9	3.92
10	0.80	9.8	1.63	9.8	0.670	9.5	1.04	10.3	0.394	10.0	1.15
23	0.187	23	1.45	23	0.141	23	0.609	23	0.084	23	0.350
49	0.058	48	0.402	48	0.040	49	0.142	48	0.016	49	0.091
90	0.015	90	0.108	90	0.008	89	0.058	90	0.004	90	0.028
138	RO	138	0.139	138	0.006	137	0.027	137	0	136	0.008
177	RO	177	0.027	181	0.002	180	0.007	180	0	182	0.004
221	0.004	215	0.018	219	0.003	220	0.005	215	0	220	M
254	RO	262	0.015	251	0.002	247	0.008	262	0	256	0.003
286	RO	288	0.014	288	0.002	290	0.005	289	0	288	0.002

Station 1.7-4, 3000 Ft. from Surface Zero, Vertical, Gage No. 20		Station 1.7-5, 1033 Ft. from Zero-in Tunnel, Horizontal Radial, Gage No. 17		Station 1.7-5, 1033 Ft. from Zero-in Tunnel, Vertical, Gage No. 14	
f	d	f	d	f	d
3.0	2.64	2.9	3.30	3.1	0.750
10.1	0.350	10.1	1.18	9.4	0.213
23	0.138	23	0.840	23	0.250
49	M	51	0.159	49	0.104
90	0.016	88	0.059	88	RO
138	0.010	138	0.014	137	0.015
181	0.003	181	M	181	0.008
221	0.002	220	0.007	214	0.007
254	0.001	260	M	250	RO
283	0	286	0.002	288	0.009

f = Frequency in cps

d = Displacement in inches

RO = Record Obscured

NV = Record Not Valid - reed went off plate

F = Reed Failed

M = Scribe Missed

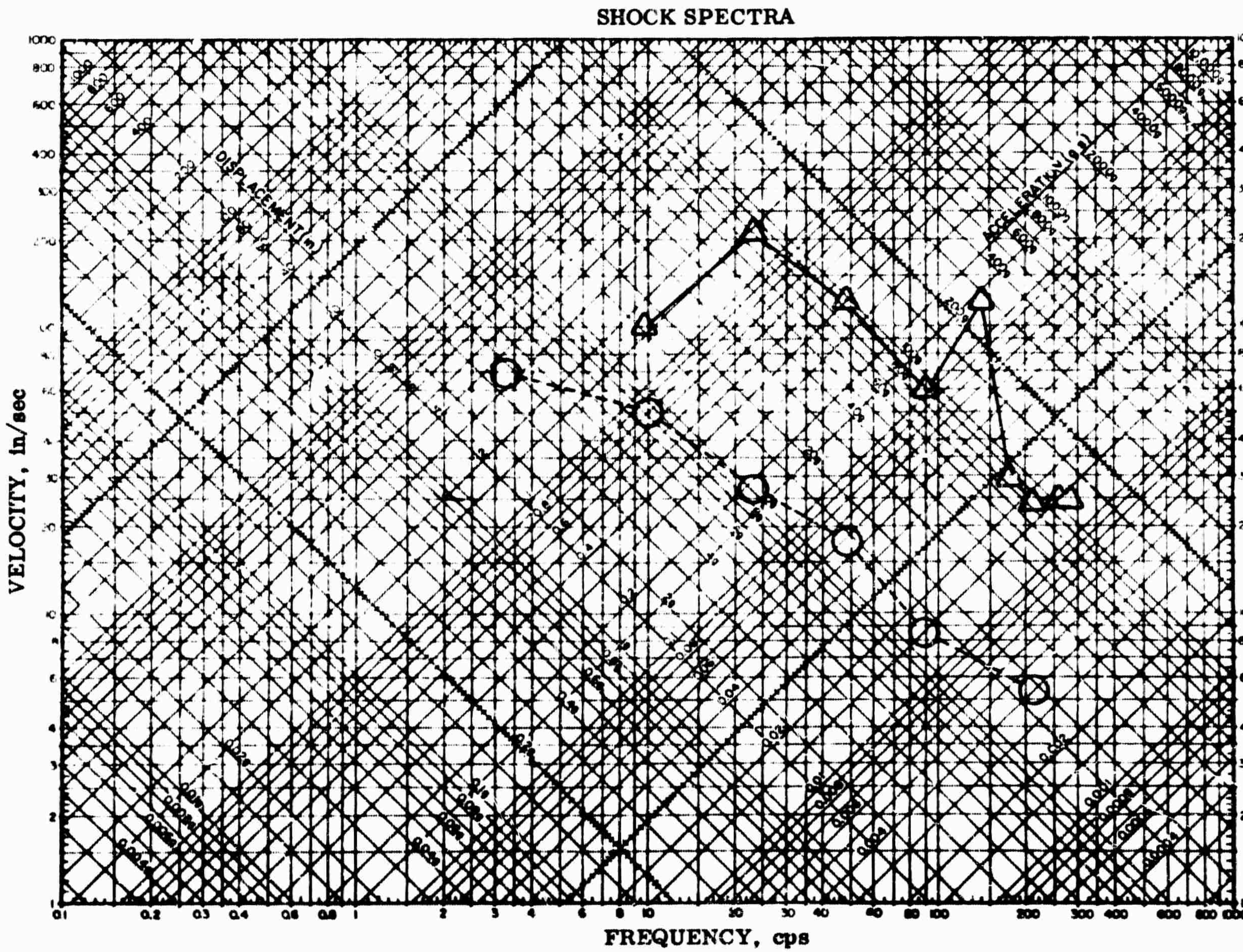

Figure 3.1 Station 1.7-1, 75 feet from surface zero, vertical Δ and horizontal radial O spectra.

SHOCK SPECTRA

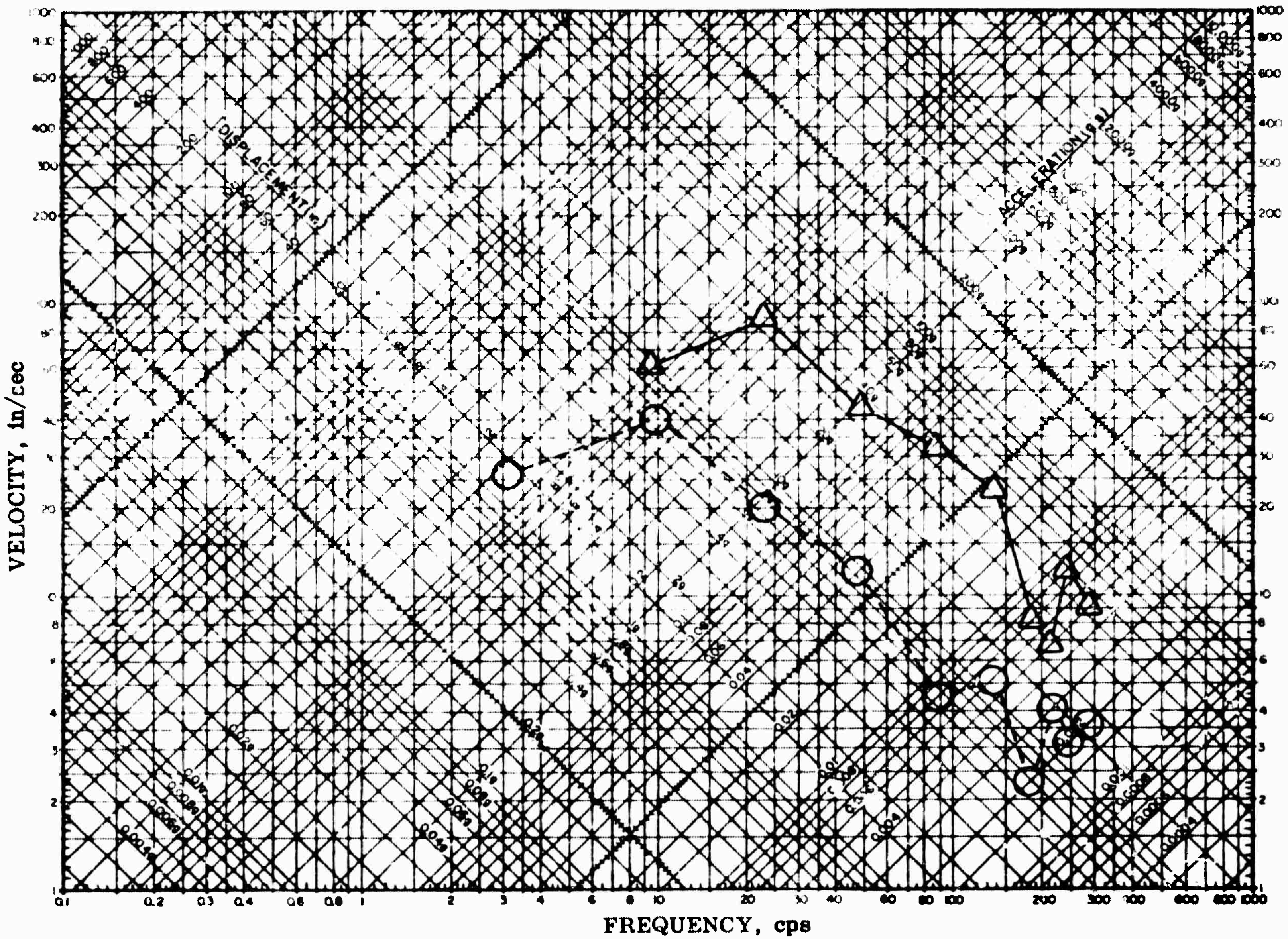

Figure 3.2 Station 1.7-2, 1000 feet from surface zero, vertical Δ and horizontal radial $\bigcirc$ spectra.

SHOCK SPECTRA

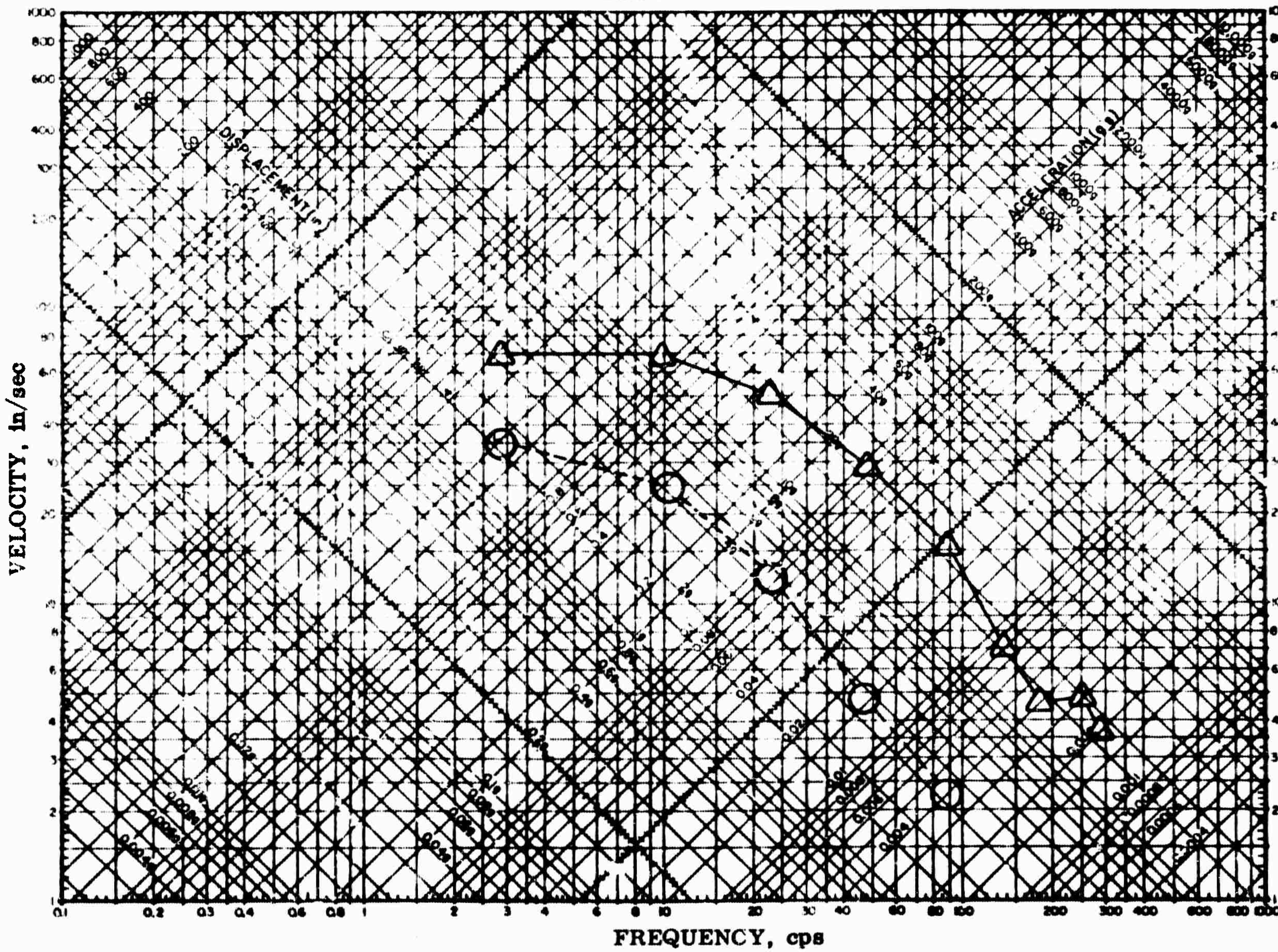

Figure 3.3 Station ..7-3, 2000 feet from surface zero, vertical Δ and horizontal radial ○ spectra.

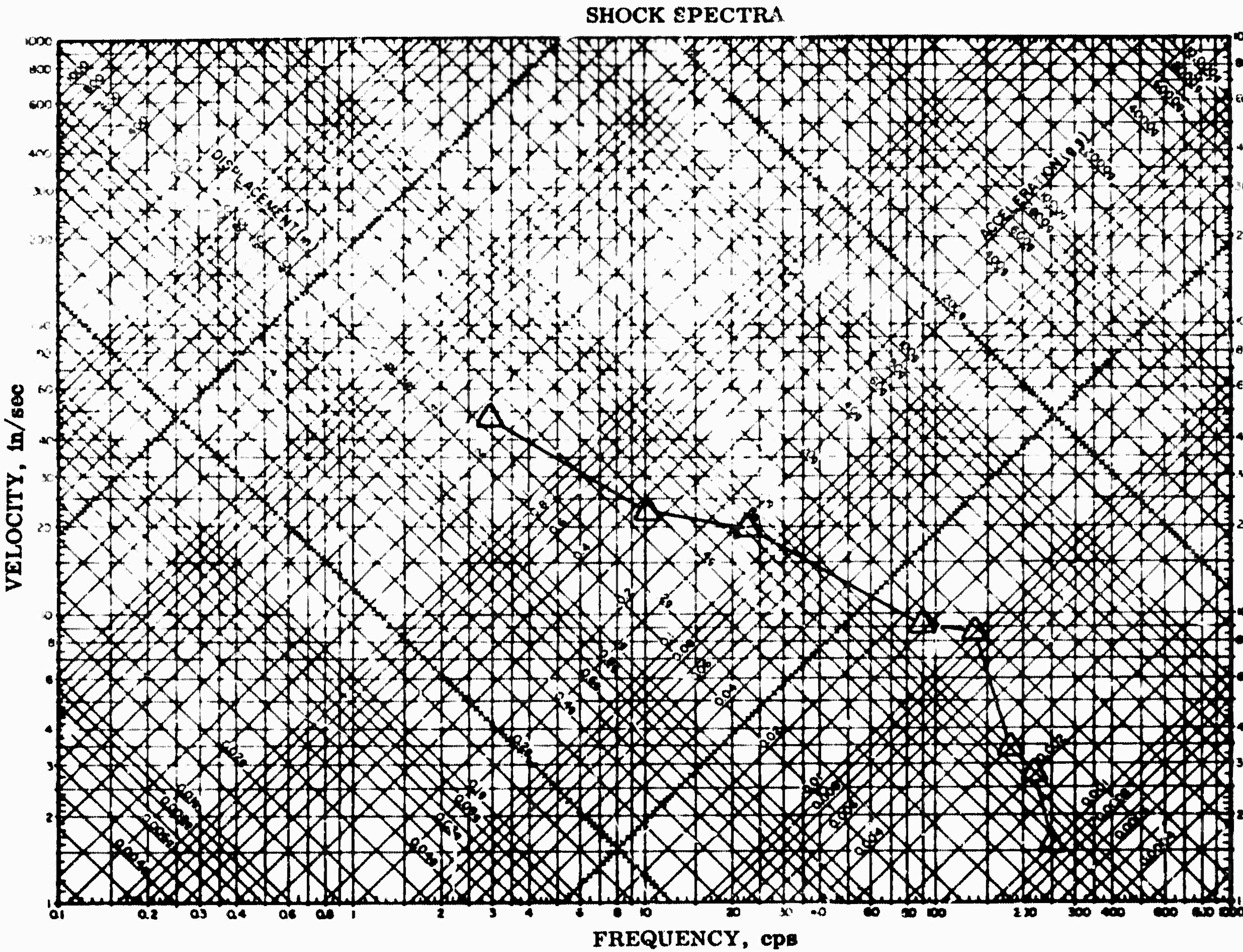

Figure 3.4 Station 1.7-4, 3000 feet from surface zero, vertical Δ spectrum.

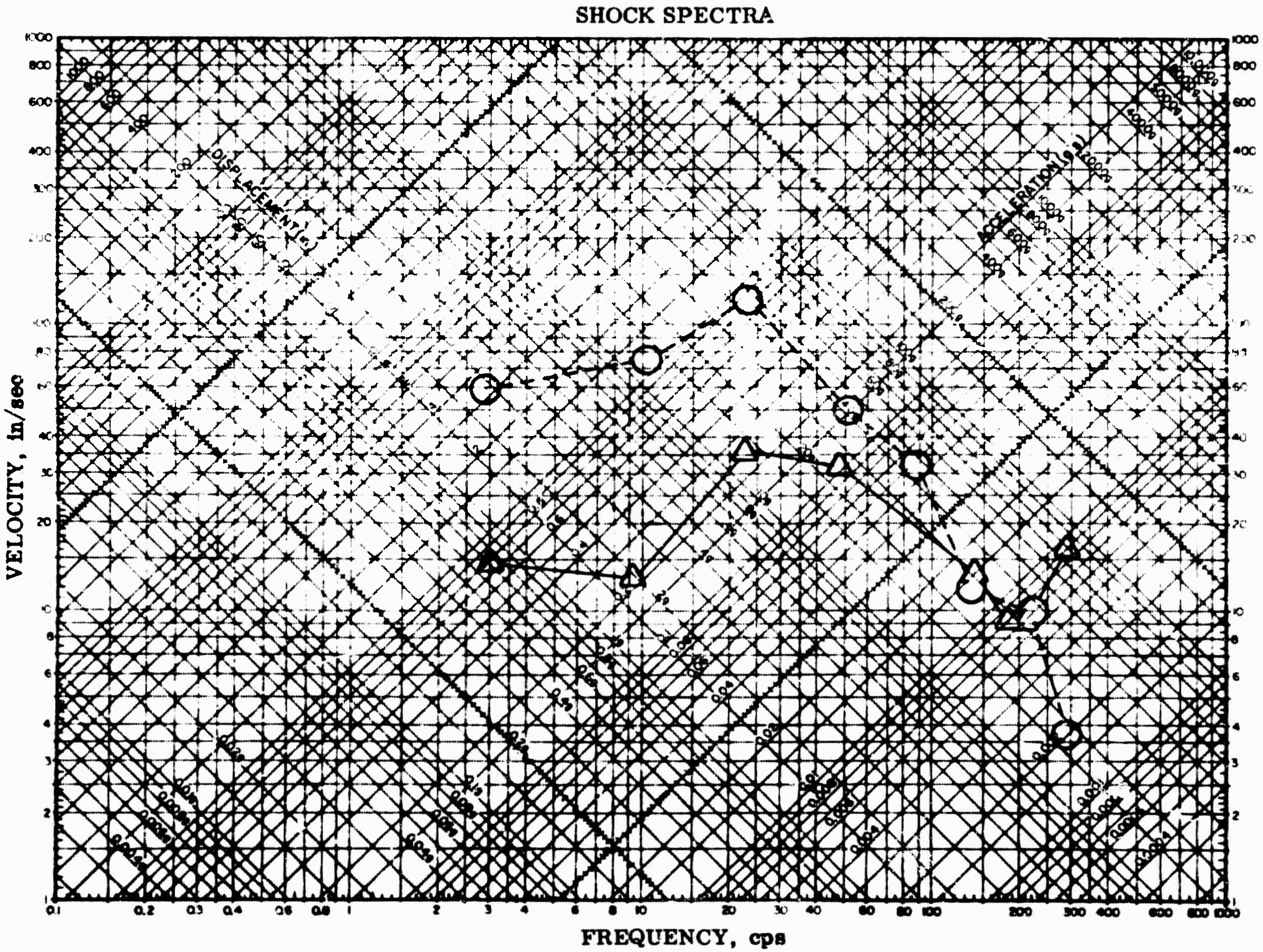

Figure 3.5 Station 1.7-5, 1033 feet from working point (in tunnel floor), vertical Δ and horizontal radial ○ spectra.

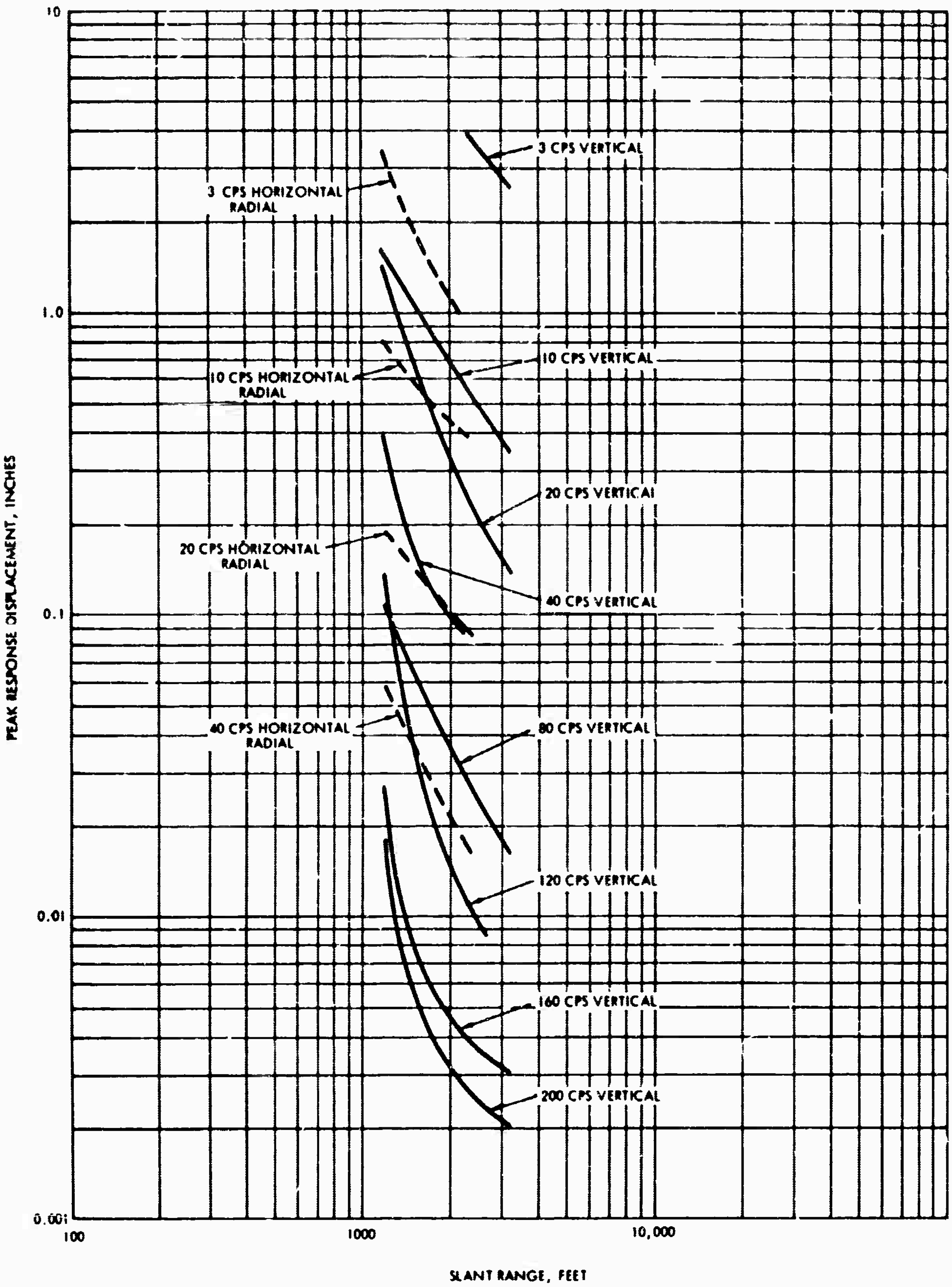

Figure 3.6 Attenuation of response displacement with range for surface gages.

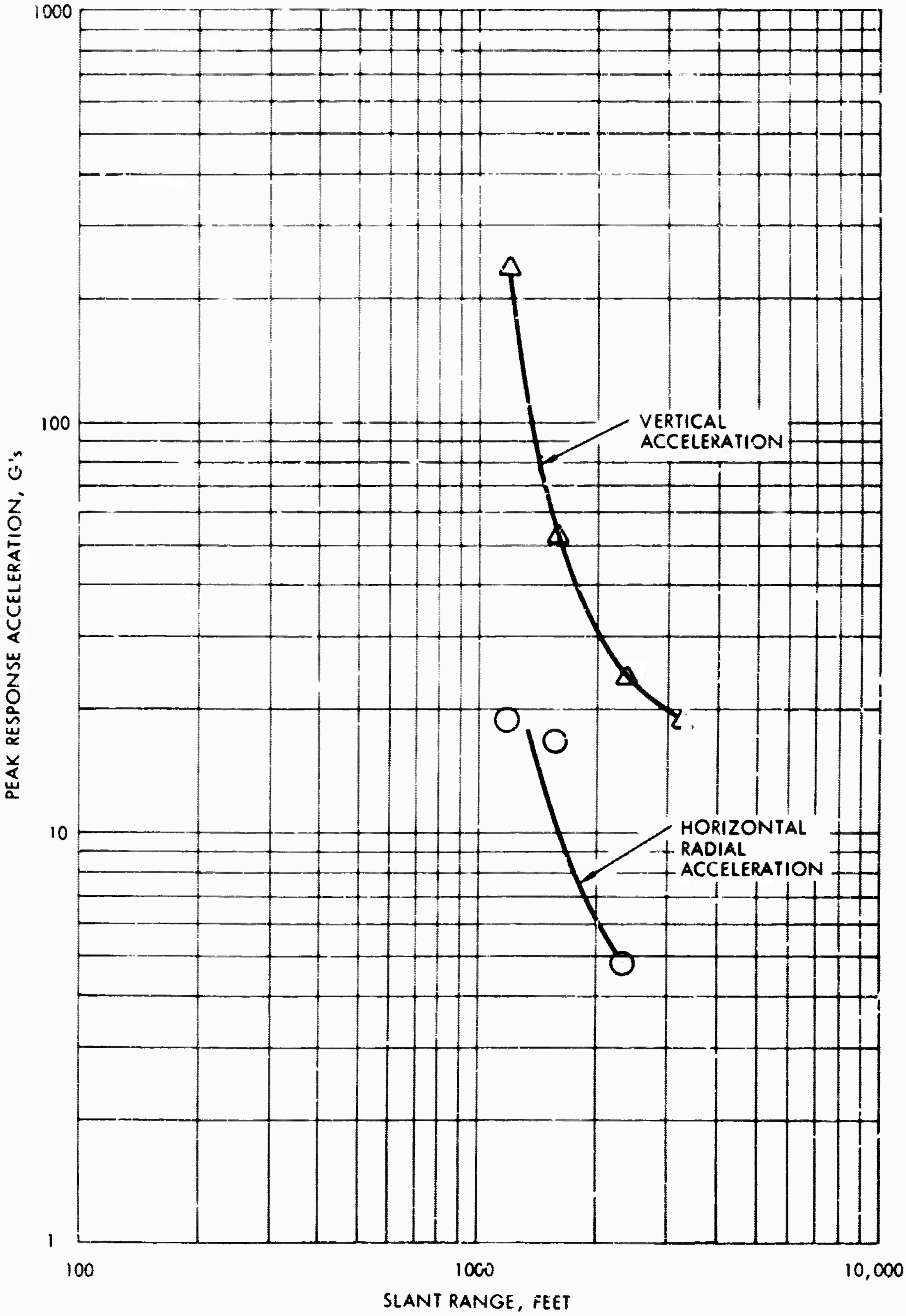

Figure 3.7 Attenuation of peak acceleration with range for surface gages.

CHAPTER 4

CONCLUSIONS

It is concluded that the project was successful in measuring the displacement ground shock spectra. Valid records were obtained from all recovered gages with the exception of the one in the IMCC mine which was too distant to record any motion. The data show the expected results, namely, the effects were reduced at greater ranges and the higher frequency response attenuated somewhat more rapidly than the lower frequency response.

REFERENCES

1. J. F. Halsey and M. V. Barton, "Spectra of Ground Shocks Produced by Nuclear Detonations (U)," Project 1.9, Operation Plumbbob, WT-1427, August 1959, Air Force Ballistic Missile Division, Air Research and Development Command, Inglewood, California, Unclassified.

2. J. F. Halsey, et al., "Ground Shock Spectra from Surface Bursts (U)," Project 1.12, Operation Hardtack, WT-1617, September 1960, Space Technology Laboratories, Inc., Los Angeles, California, Secret Formerly Restricted Data.

3. M. V. Barton, J. F. Halsey, and F. A. Pieper, "Ground Shock Spectrum Measurements, 20-Ton High Explosive Test," STL Report STL/TR-60-PD01-19295, 1 September 1960, Space Technology Laboratories, Inc., Los Angeles, California, Unclassified.

4. J. F. Halsey and M. V. Barton, "Ground Shock Spectrum Measurements - 100-Ton High Explosive Test," STL Report 6120-0039-RU000, 15 September 1961, Space Technology Laboratories, Inc., Los Angeles, California, Unclassified.

5. M. V. Barton, J. F. Halsey, and F. A. Pieper, "Ground Shock Spectrum Measurements, 500-Ton High Explosives Test," TRW Space Technology Laboratories, Redondo Beach, California, 21 November 1960, Unclassified.

6. M. V. Barton, F. A. Pieper, and R. W. Sauer, "Displacement Spectrum Measurements," Project 3.12, Operation Nougat, POR-1806, Hard Hat Event, STL Report 8610-6011-RU-000, December 1962, TRW Space Technology Laboratories, Redondo Beach, California, Confidential.

7. M. V. Barton, F. A. Pieper, and F. W. Galbraith, "Preliminary Report, Shock Spectrum Measurements, Project Shoal," Project 1.7, STL Report 8610-6014-TU-000, 11 November 1963, TRW Space Technology Laboratories, Redondo Beach, California, Unclassified.

8. F. W. Galbraith, "Ground Shock Spectrum Measurements, Carp and Clearwater Events," STL Report 5118-6001-RU-000, 29 October 1963, TRW Space Technology Laboratories, Redondo Beach, California, Unclassified.

9. F. A. Pieper, et al., "Shock Spectrum Measurements," Project 1.7 Final Report, VUF-2400, STL Report 8610-6015-RL-000, TRW Space Technology Laboratories, Redondo Beach, California, Confidential.

10. M. V. Barton and J. M. Lindahl, "Shock Spectrum Measurements," Project 1.7 Preliminary Report, VUP-2401, June 1962, TRW Space Technology Laboratories, Redondo Beach, California, Unclassified.